Generalized voltage Droop Control with Inertia Mimicry Capability – Step Towards Automation of Multi-terminal HVDC Grids

Kumars Rouzbehi[1], Jiebei Zhu[2], Weiyi Zhang[1], G.B Gharehpetian[3], Alvaro Luna[1], and Pedro Rodriguez[1,4]

(1) Technical University of Catalonia, Spain *(2) Network Strategy Group, National Grid, UK*
(3) Amirkabir University of Technology, Iran *(4) Abengoa Research, Abengoa , Spain*

kumars.rouzbehi@upc.edu, jiebei.zhu@nationalgrid.com, weiyi.zhang@estudiant.upc.edu, grptian@aut.ac.ir, luna@ee.upc.edu, prodriguez@ee.upc.edu

***Abstract*—the level of inertia in modern power systems is reducing drastically due to the increasing penetration of renewables to the power grid. In the near future the grid will face high penetration of renewable resources because of countries policies. However, renewables provides no inertia. On the other hand, voltage source converter (VSC) based multi terminal HVDC system is a promising solution for connection of offshore wind farms to transmit huge amount of harvested energy to ac grids.**

This paper proposes a complete VSC-HVDC control structure which enables candidate converter station to mimic the inertia of a synchronous machine considering generalized voltage droop strategy. The emulated inertia comes from the capacitor of the dc link. The proposed strategy enables a VSC station with a fixed dc link capacitor to mimic inertia constant in a considerable range, by configuring a range of dc-link dc voltage variation. Sudden load changes in weak ac grid will be compensated by the emulated inertia that is provided by the candidate grid side VSC station.

Keywords—Generalized voltage droop; Inertia mimicry; MTDC grid; VSC;

I. Introduction

Generations based on renewables such as wind or PV are normally attached to the grid through power electronic converters, which decouple the electrical power from the mechanical system and intrinsically perform as electrical power sources without "inertia" [1]–[3]. The generated power of wind turbines is controlled by the attached converter stations, thus decouple the mechanical speed of the turbine rotor and the frequency of the ac grid of the wind farm.

On the other hand, regarding the harvested power transmission in multi-terminal dc (MTDC) grids, the VSC stations, which integrate offshore wind farms to the onshore ac electrical networks, have not any contribution in inertia to the connected ac grid. It means that the wind generation system appears "inertia-less" in the ac electrical networks. Even if there is supporting spinning reserve stored in the rotating mass available at the other terminals of the MTDC system, the VSC stations actually decouples the available kinetic energy from one ac system to another.

In traditional electrical grids, the ac system inertia comes from the aggregate of classical synchronous generators which dominate the ac system. This in turn makes the system less vulnerable to short term power imbalances which are caused by sudden generation or loads changes [4]–[5].

By increasing the number of grid-connected power converters in modern power systems of future, it will result in decreasing of the total system inertia and hence lead to more significant frequency perturbations. In the meantime, generation plants based on wind farms with variable speed turbines encounter the same problem. A solution to mitigate this impact is proposed in [4].

In an attempt to address this critical issue, several inertia mimicry control strategies for wind power generators have been proposed [6]–[9]. These strategies enable wind power generators to contribute inertia during ac grid disturbances. The authors in [7] studied the dynamic contribution of DFIG to provide an inertial response. However, the authors stated that DFIG turbines may stall if excessive energy is drawn from the rotor. Reference [8] proposes a control scheme for fully rated, converter-interfaced, PMSG wind generators that can provide frequency support/control capability. This is achieved by controlling the VSC output power according to the rate of change in grid frequency. The disadvantage with this scheme is that the recovery of the rotor speed can be difficult after a deceleration of the machine rotor.

This paper proposes a control solution for VSC stations in MTDC grids, which integrate the inertia mimicry capability in the generalized voltage droop (GVD) controller proposed in [11]. It is implemented in VSC control stations and exploits the energy stored in the dc link capacitors to emulate inertia. The controlled VSC will support the ac network during disturbances, with minimal impact on the systems connected beyond the terminals of the MTDC system. The proposed strategy is capable of emulating a wide range of inertia time constants using relatively small constant capacitances connected to the dc link. Moreover, this paper investigates the proposed approach oriented to weak and low-inertia ac systems. Low-inertia systems are deemed to have insufficient number of rotating machines. Examples of such applications are MTDC grid feeding an island system, or interface wind farms. It also appears in scenarios when the MTDC grid operates in island mode after disconnecting from the ac mains because of the trips of ac transmission lines, or black-start after blackout. In this time, the control structure makes the "hidden inertia" available to the grid so that a candidate VSC can emulate inertia and provide efficient support to the primary grid frequency control.

This paper is organized as follows. Section II presents the traditional control paradigm of VSC for MTDC grids and the GVD control. The inertia mimicry control is presented in section III. Preliminary simulation results are presented in section IV, and conclusions are drawn in section V.

II. VSC Control in MTDC Grids

Primary control of MTDC grids includes dc voltage regulation at the dc terminals, control of active and reactive power at the point of common coupling (PCC) and maintaining the PCC's ac voltage at the specified set point. The most commonly used control strategy for the VSC-HVDC stations is based on the vector control [10]–[12]. In this strategy the ac currents and voltages of the converter station (at the PCC) are transformed into the rotating direct-quadrature (dq) reference frame, synchronized with the ac grid voltage by means of a phase-locked loop (PLL). This structure permits to carry out a decoupled control of the active and reactive powers as well as the dc and ac voltages. The general architecture of the vector control at a VSC-HVDC station is illustrated in Fig. 1. The outer controllers showed in Fig. 1 are used for generating the reference currents for the inner current loop, which determines the voltage reference of the converter in the dq frame.

A. Inner Current Controller

The inner current controller (ICC), includes fast proportional-integral (PI) controllers which track the reference currents, set by the outer controllers, and generates the voltage reference for the VSC [10], [11].

To derive the structure of the ICC, the voltage at PCC (e_s) and converter-side voltage (v_c) of Fig. 1 are related by,

$$v_{ac} - v_c = R_T i_c + L_T \frac{di_c}{dt} \tag{1}$$

where, i_c is the current flowing from the ac grid to the converter and R_T and L_T show the total resistor and inductor installed between the PCC and the VSC. Then by applying the dq transformation, (1) can be expressed in dq reference frame by,

$$e_d - v_d = R_T i_d + L_T \frac{di_d}{dt} - \omega L_T i_q \tag{2a}$$

$$e_q - v_q = R_T i_q + L_T \frac{di_q}{dt} + \omega L_T i_d \tag{2b}$$

where, ω is the angular frequency of the ac voltage measured at the PCC. The reference voltages ($v_{d,ref}$ and $v_{q,ref}$), produced by ICC, are then transformed back into the abc reference frame and used to generate the switching signal of

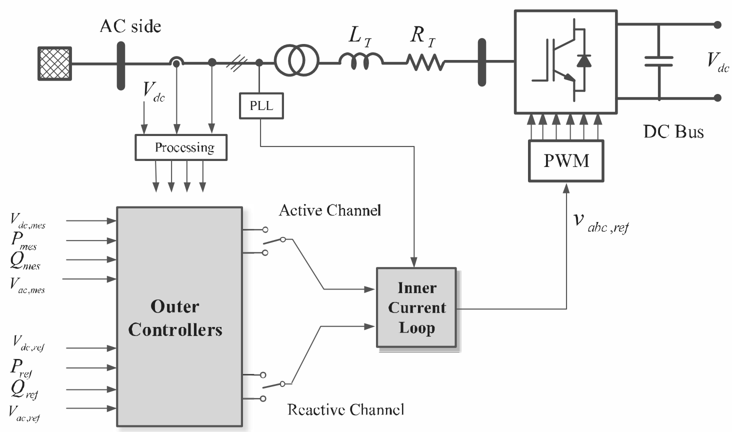

Fig. 1. General architecture of the vector control for a VSC-HVDC station.

the converter.

B. Outer Controllers

The outer controllers include the active and reactive channels, as shown in Fig. 2. The active channels are responsible for regulating the active power and the dc voltage, while the reactive channels control the reactive power or amplitude of the ac voltage at the PCC.

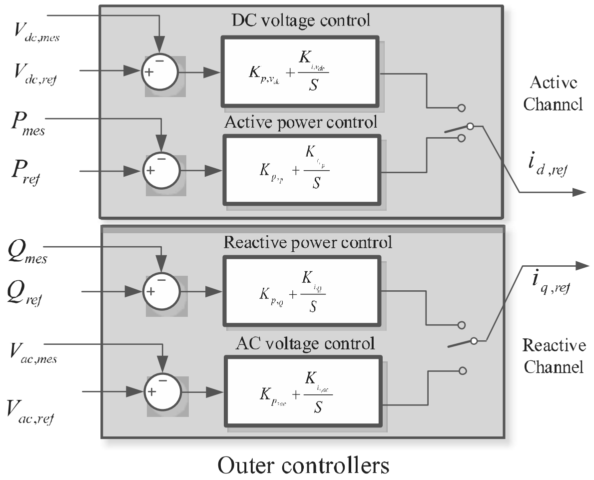

Fig. 2. Structure of the outer controller.

For active power control, the power equations in dq reference frame can be written as:

$$P = v_d i_d + v_q i_q \tag{3}$$

$$Q = v_q i_d - v_d i_q \tag{4}$$

It is worth noting that the d-axis of the dq frame is aligned with the ac network voltage phasor through a PLL; i.e., e_q=0 and hence,

$$P = v_d i_d \tag{5}$$

$$Q = -v_d i_q \tag{6}$$

Based on (5) and (6), the currents in d and q axes can be used to control active and reactive powers, respectively.

The ac voltage controller is intended to regulate the amplitude of the PCC's ac voltage. This can be accomplished by injecting the required amount of reactive power such that the ac voltage at the PCC matches the reference value. Hence, the control of the ac voltage is carried out by modifying the q-axis current.

Likewise, to keep the dc voltage at its reference value, the active power exchanged with the ac grid must be properly regulated. Hence, modification of the d-axis current (i_d) allows to control the dc voltage within the permissible limits.

Vector current control technique has been used in control of VSC-HVDC systems to achieve fast current control. With the constant power control, the processed power of the VSC-HVDC station can be precisely controlled to track the reference value, in spite of the frequency variations of the interconnected grids. In this way, the dynamic characteristics of the VSC is significantly different from the synchronous machines. The frequency perturbations in one grid is hence isolated from the other grid considerably, which improves the security of the grid operation [13].

C. Generalized Voltage Droop Control

The GVD control is proposed as a generalized design integrating droop control, dc voltage control and fixed power control. It is able to perform fixed power control, fixed dc voltage control or share power among voltage-regulating converters based on the slopes of voltage droop characteristics, hence shows more flexibility than the conventional voltage droop scheme that is only capable of power-voltage droop control.

It involves three operating modes as shown in Fig. 3, where each mode can be activated by adjusting the coefficient of the generalized voltage droop characteristic, thus offers the possibility of smooth switching among each mode. In this way, the role of a specific VSC is not necessarily fixed during the operation and can smoothly change along with the needs of the system, and the reliability of the system is enhanced as well as the flexibility in secondary control.

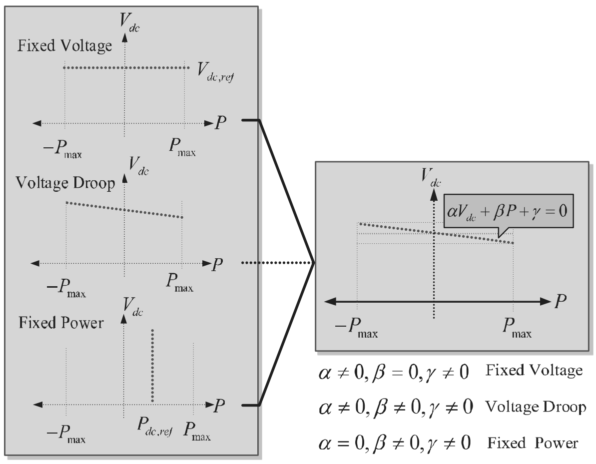

Fig. 3. GVD characteristics with three operation modes.

The GVD characteristic is mathematically expressed by,

$$\alpha V_{dc,meas} + \beta P_{meas} + \gamma = 0 \tag{7}$$

where, $V_{dc,meas}$ and P_{meas} are the measured voltage and power at dc-side of the VSC, respectively and α , β and γ are the coefficients of the GVD characteristics.

III. VSC Inertia Mimicry Control

Oriented to weak grids, it is necessary to specify the characteristics of the grid-connected VSC in order to maintain connection and further contribute inertia behavior under contingencies such as sudden load changes or grid faults [15]. In this design, specific amount of inertia is going to be incorporated in a voltage source converter in multi-terminal HVDC grid to support a weak ac grid in case of contingencies.

A. Inertia Mimicry Algorithm

In physics, “inertia” is defined as the amount of resistance to change velocity. For a synchronous generator all the rotating masses connected to the shaft can be quantified by an inertia time constant H_{ac}. The unit of H_{ac} is seconds, which corresponds to the time period it takes to accelerate rotating masses from the speed of zero to the rated speed using full rated power, and it is given as:

$$H_{ac} = \frac{0.5 J \omega_m^2}{S_{SG}} \tag{8}$$

Where J is the moment of inertia of the system, and ω_m indicates the mechanical rotational speed of the machine.

The well-known equation of synchronous machine angular motion is given by:

$$f^{\bullet} = \frac{f_0}{2H_{ac}S_{SG}}(P_m - P_e) \tag{9}$$

Where P_m and P_e are respectively the mechanical input power and the electrical output power of the machine, and f_0 is the nominal frequency of the ac grid.

Or in per unit of power:

$$f^{\bullet} = \frac{f_0}{2H_{ac}}(P_m - P_e) \quad \text{(p.u.)} \tag{10}$$

Keeping the terms P_m and P_e to represent the power flowing in and out of the equivalent capacitor seen at the dc link of grid side VSC, the relation between the non-linear dynamics of the dc-bus voltage and the power unbalance can easily be obtained as follow,

$$C_t V_{dc} V^{\bullet}_{dc} = P_m - P_e \tag{11}$$

where C_t is the equivalent capacitance if the dc link.

(11) can be transformed to (12) expressed in per unit of power:

$$V^{\bullet}_{dc} = \frac{S_{VSC}}{C_t V_{dc}}(P_m - P_e) \quad \text{(p.u.)} \tag{12}$$

To give inertia mimicry behavior to the VSC and assign it by a specific constant H_{dc}, the power variation of synchronous generator can be equated to the power variation on dc capacitor of VSC [14].

(13) and (14) are obtained by transforming (10) and (12) respectively.

$$f^{\bullet} \cdot \frac{2H_{ac}}{f_0} = (P_m - P_e) \tag{13}$$

$$V^{\bullet}_{dc} \cdot \frac{C_t V_{dc}}{S_{VSC}} = (P_m - P_e) \tag{14}$$

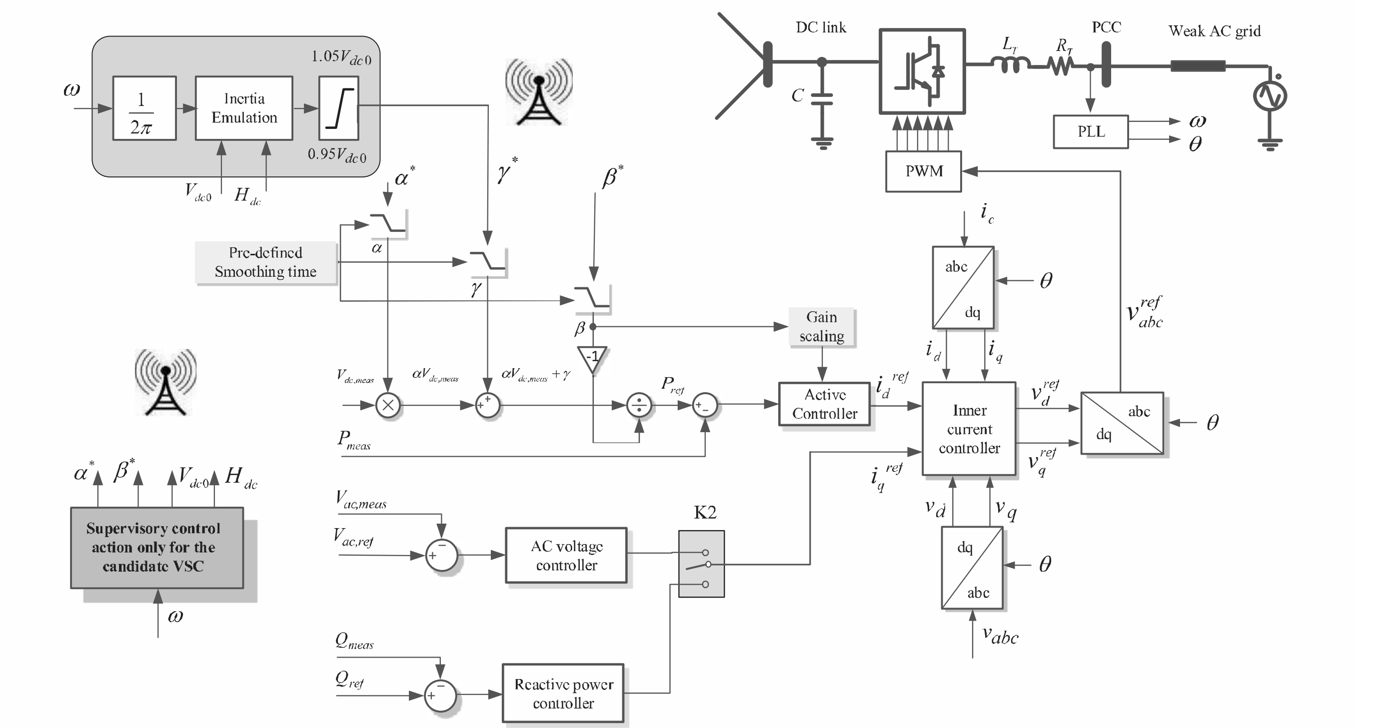

Fig. 4. Overall control scheme for candidate VSC stations in MTDC grids for inertia mimicry.

Then, (15) is obtained by combining (13) and (14).

$$f^{\bullet} \cdot \frac{2H_{dc}}{f_0} = V_{dc}^{\bullet} \cdot \frac{C_t V_{dc}}{S_{VSC}} \tag{15}$$

Moreover, (15) can be shown in terms of time as (16),

$$\frac{2H_{dc}}{f_0} \cdot \frac{df}{dt} = \frac{C_t V_{dc}}{S_{svc}} \cdot \frac{dV_{dc}}{dt} \tag{16}$$

By integrating both sides of (9), (17) is obtained.

$$\frac{2H_{dc}}{f_0} \cdot f = \frac{C_t V^2{}_{dc}}{2S_{vsc}} + K \tag{17}$$

The constant K can be calculated according to the values of the nominal operating point as shown in (18).

$$\begin{aligned} K &= \frac{2H_{dc}}{f_0} \cdot f_0 - \frac{C_t V^2{}_{dc0}}{2S_{vsc}} \\ &= 2H_{dc} - \frac{C_t V^2{}_{dc0}}{2S_{vsc}} \end{aligned} \tag{18}$$

By substituting K in (17) with (18), (19) is obtained.

$$\frac{2H_{dc}}{f_0} \cdot f = \frac{C_t}{2S_{vsc}} \cdot V^2{}_{dc} + 2H_{dc} - \frac{C_t V^2{}_{dc0}}{2S_{vsc}} \tag{19}$$

Therefore, in order to have specified inertia of H_{dc}, the relation between the dc link voltage V_{dc} and ac grid frequency f needs to yield (19).

B. Control Implementation

This inertia mimicry algorithm can be easily implemented based on the GVD control architecture for MTDC-VSC as shown in Fig. 4, which is refereed as GVD-IE control in this paper. Instead of using the traditional controllers to generate the reference for outer controllers, the inertia mimicry algorithm (19) is adopted to generate the dc voltage reference. Therefore, the dc voltage reference is calculated based on (20), which is obtained by transforming (19).

$$V_{dc}^{ref} = \sqrt{\frac{4H_{dc}S_{vsc}}{C_t f_0} f + (V^2{}_{dc0} - \frac{4H_{dc}S_{vsc}}{C_t})} \tag{20}$$

Specified amount of inertia can be given by assigning the value of H_{dc} and generate the dc voltage reference according to (20).

In MTDC grids the maximum variation of dc bus voltage of VSC stations is considered ±.05 p.u. of nominal value in normal condition, nevertheless, in case of contingencies it can be considered in the range of ±.1 p.u. of nominal value. Taking these requirements into account, the calculated value of V_{dc}^{ref} needs to be processed through a limiter.

Then the overall control scheme for the MTDC grid is shown in Fig. 5.

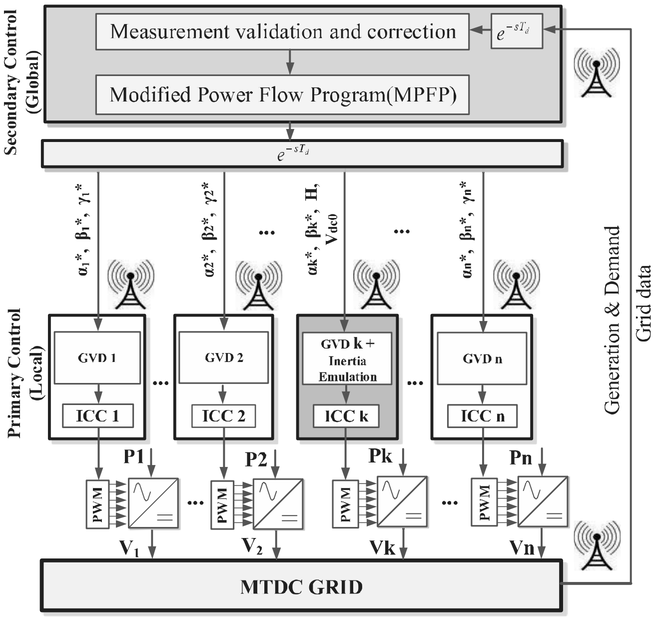

Fig. 5. Overall control structure for MTDC grid.

In the extended version of this paper, the proposed control solution will be validated in the MTDC testing benchmark – CIGRE model as shown in Fig. 6.

C. Operation modes of the poroposed control structure

Two separate operation modes can be realized by GVD-IE controlled station based on the signals received from supervisory control system of the MTDC grid. The operation modes are,

1- *Normal GVD operation*

In this mode the controlled VSC station can operate in droop control mode, fixed dc voltage or fixed power control mode. And the H_{dc} needs to be set to 0, while V_{dc0}, α^*, β^* are set according to the secondary power flow program. The parameter V_{dc0} can be specified like the parameter in the original GVD control [11].

2- *Inertia mimicry mode*

In this mode, converter will behave like a synchronous generator providing specified amount of inertia that is governed by supervisory control center. And for this mode the GVD controller should be set in the dc voltage control mode, where β^* is set to a significantly reduced value. And instead of setting a fixed dc voltage reference in the original GVD control, the reference is set according to the inertia algorithm in the GVD-IE control.

IV. CONCLUSION

In this paper a complete control structure for automation of MTDC grid considering inertia mimicry for candidate VSC station is designed and presented. Inertia mimicry technique is integrated to generalized voltage droop control of MTDC grid to take one step forward for the automation of the future MTDC grids.

In this paper an analytical approach is considered and in the extended work of the paper some scenarios will be simulated to show the eligibility of the control framework.

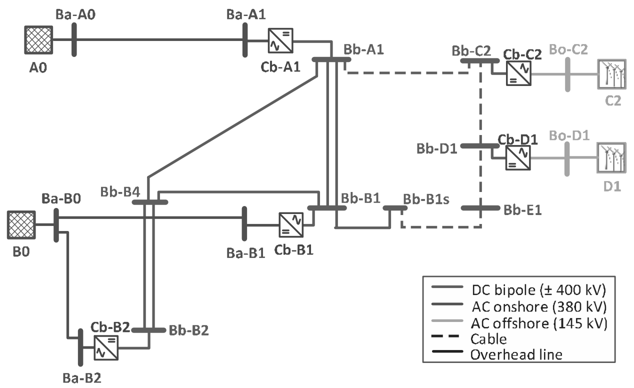

Fig. 6. Simulated plant based on CIGRE MTDC test system.

V. REFERENCES

[1] M. P. N. van Wesenbeeck, S. W. H. de Haan, P. Varela, and K. Visscher,"Grid Tied Converter with virtual kinetic storage,"*in Proc. 2009 IEEE Power Tech Conf.*, Romania, 28 June – 2 July 2009, pp.1– 7.

[2] H.-P. Beck, and R. Hesse, "Virtual Synchronous Machine," *Proc. 9th Int. Conf. Elec. Pow. Quality Utilisation*, Barcelona, Spain, 9– 11 October 2007, pp. 6.

[3] J. Machowski, J. W. Bialek, J. R. Bumby, "*Power System Dynamics and Stability*," Chichester, UK, Wiley, 1997, Chapter 5.

[4] J. Morren, J. Pierik, and S.W.H. De Haan,"Inertial response of variable speed wind turbines," *Electric power systems research*, pp.980–987, 2006.

[5] T.K. Vrana, R.E. Torres-Olguin, B. Liu, and T. M. Haileselassie. "The North Sea Super Grid - A Technical Perspective". *9th Int. Conf. AC DC Power Trans.*, London, 2010.

[6] M.Kayikci and J.V.Milanovic, "Dynamic contribution of DFIG-based wind plants to system frequency disturbances," *IEEE Trans. Power Syst.*, vol. 24, no. 2, pp. 859–867, May. 2009.

[7] J. F. Conroy and R. Watson, "Frequency response capability of full converter wind turbine generators in comparison to conventional generation," *IEEE Trans. Power Syst.*, vol. 23, no. 2, pp. 649–656, May 2008.

[8] M. Zhixin, F. Lingling, D. Osborn, and S. Yuvarajan, "Wind farms with HVdc delivery in inertial response and primary frequency control," *IEEE Trans.Energy Convers.*, vol. 25, no. 4, pp. 1171–1178, Dec. 2010.

[9] K. Clark, N. W. Miller, and J. J. Sanchez-Gasca, 2009, "Modeling of GE wind turbine-generators for grid studies," Aug. 2011. [Online]. https://www.researchgate.net/publication/267218696_Modeling_of_GE_Wind_Turbine-Generators_for_Grid_Studies_Prepared_by(visited on 22/08/2015).

[10] K. Rouzbehi, A. Miranian , A. Luna, and P. Rodriguez, "Optimized control of multi-terminal dc grids using particle swarm optimization," *EPE journal* ,vol. 24, no. 2, 2014.

[11] K. Rouzbehi, A. Miranian , J. Candela, A. Luna, and P. Rodriguez, "A generalized voltage droop strategy for control of multi-terminal dc grids," *IEEE Trans. Ind. Appl.,* vol.51, no.1, pp.607–618, Jan./Feb. 2015.

[12] K. Rouzbehi, A. Miranian , A. Luna, and P. Rodriguez, "DC voltage control and power-sharing in multi-terminal dc grids based on optimal dc power flow and voltage droop strategy," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol.2, no.4, pp.1171–1180, Dec. 2014.

[13] M. Guan, W.Pan, J.Zhang, Q. Hao, J.Cheng and X. Zheng,"Synchronous generator Emulation control strategy for voltage source converter (VSC) stations," *IEEE Trans. Power Syst.*, vol.30, no.6, pp.3093–3101, Nov. 2015.

[14] K. Rouzbehi, C. Gavriluta, J. Candela, A. Luna and P. Rodriguez, "Comprehensive analogy between conventional AC grids and DC grids characteristics," IECON 2013, pp.2004–2010, 10–13 Nov. 2013

[15] Jiebei Zhu, C.D. Booth, G.P. Adam, A.J.Roscoe,and C.G. Bright, "Inertia Emulation Control Strategy for VSC-HVDC Transmission Systems, " *IEEE Trans. Power Syst.,* , vol.28, no.2, pp.1277–1287, May 2013.